THE MEMS KNUDSEN COMPRESSOR AS A VACUUM PUMP FOR SPACE EXPLORATION APPLICATIONS

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Abstract

Several lander, probe and rover missions currently under study at the Jet Propulsion Laboratory (JPL) and especially in the Microdevices Laboratory (MDL) Center for Space Microelectronics Technology, focus on utilizing microelectromechanical systems (MEMS) based instruments for science data gathering. These small instruments and NASA's commitment to "faster, better, cheaper" type missions has brought about the need for novel approaches to satisfying mission requirements. Existing in-situ instrument systems clearly lack novel and integrated methods for satisfying their vacuum needs. One attractive candidate for a MEMS vacuum pump is the Knudsen Compressor, which operates based on thermal transpiration. Thermal transpiration describes gas flows induced by temperature differences maintained across orifices, porous membranes or capillary tubes under rarefied conditions. This device has two overwhelmingly attractive features as a MEMS vacuum pump - no moving parts and no fluids. An initial estimate of a Knudsen Compressor's pumping power requirements for a surface atmospheric sampling task on Mars is less than 80 mW, significantly below than alternative pumps. Due to the relatively low energy use for this task and the applicability of the Knudsen Compressor to other applications, the development of a Knudsen Compressor utilizing MEMS fabrication techniques has been initiated. This paper discusses the initial fabrication of a single-stage MEMS Knudsen Compressor vacuum pump, provides performance criteria such as pumping speed, size, energy use and ultimate pressure and details vacuum pump applications in several MDL related in-situ instruments.

I. Introduction

NASA's new era of "faster, better, cheaper" missions have brought about the need for novel approaches to satisfying mission requirements. The success of these new missions will undoubtedly rely on the advantages microelectromechanical systems (MEMS) provide. Existing in-situ instrument systems clearly lack novel and integrated methods for satisfying their vacuum needs. One such device is the miniaturized mass spectrometer currently under development at the Jet Propulsion Laboratory's (JPL) Microdevices Laboratory (MDL). This mass spectrometer utilizes a micromachined quadrupole array for gas composition analyses. It is capable of providing the same mass resolution and mass range as a commercial large-scale unit but with 20 times less mass, 75 times less power and 135 times less volume. However, the miniaturized mass spectrometer system lacks a vacuum pump that can meet the demanding mission requirements of small mass and volume and low power use. The Knudsen Compressor is one attractive candidate for the mass spectrometer's gas-handling needs.

Knudsen Compressors have two overwhelmingly attractive features for MEMS vacuum pumps - no moving parts and no fluids. Initial estimates of low power usage and numerous possible device applications have led to the development of a micromechanical design for a single stage Knudsen Compressor.

This single stage device is the first implementation using MEMS fabrication techniques and will lead to the development of a Knudsen Compressor cascade capable of providing the gas-handling requirements of the miniaturized mass spectrometer or other MEMS in-situ instruments.

II. Background and Motivation

Thermal transpiration, which is a rarefied gas dynamic phenomenon studied extensively in the early 1900s, is the basis for Knudsen Compressor operation. The results of thermal transpiration may be illustrated by considering two volumes of gas separated by a thin membrane containing many holes in which the typical dimension of the holes is small compared to the mean free path of the gas. For this condition the system is considered to be free-molecular, which implies that molecule-molecule collisions can be neglected and molecule-surface collisions dominate the system interactions. If the two volumes are maintained at temperatures T_1 and T_2, but are otherwise undisturbed, the equilibrium pressures p_1 and p_2 of the two volumes are related by $p_1/p_2 = \sqrt{(T_1/T_2)}$. In each tube (i.e. hole in the membrane) there is a flow of gas along the tube's inner surface towards the hot end and a pressure driven return flow in the central portion of the tube. In many cases rarefied phenomena tend to be laboratory curiosities at normal dimensions and correspondingly low pressures. However, in the micromechanical domain they can form the basis for important systems because the phenomena appear at much higher pressures due to characteristically smaller dimensions. The Knudsen Compressor demonstrated by Vargo et. al.[1] and discussed in this paper is a modern version of the original thermal transpiration compressor described by Knudsen.

Nearly ninety years ago, Knudsen demonstrated a compression ratio of ten using a series of tubes each of which contained a small diameter constriction across which a temperature gradient was maintained. Due to technological constraints, his device was limited to operations far below atmospheric pressure. The recent, serendipitous availability of small pore membranes in materials with low thermal conductivity has significantly expanded the Knudsen Compressor's potential applicability. These engineered nanopore materials allow the construction of a thermal transpiration-driven compressor that can operate under free-molecular conditions over a much wider and more useful pressure range (from mTorr to near atmospheric pressures). Energy dissipation is a major concern in densely packed micromechanical systems. Parasitic thermal losses inherent to thermal transpiration dominate the design as opposed to conventional macroscopic compressors in which flow processes dominate. The Knudsen Compressor tends to be thermally inefficient, but this can be made tolerable and is more than balanced by the attraction of a vacuum pump with no moving parts - a distinct advantage for micromechanical devices. Since no fluids or lubricants are required by a Knudsen compressor it is also ideally suited for operation in space exploration applications or other type of severe environment.

The MEMS Knudsen Compressor vacuum pump development at JPL is motivated by the need for vacuum pumps in MEMS-based in-situ instruments. Gas-sampling based and other types of instruments require vacuum pumps in order to function. Integration of a MEMS-based vacuum pump within existing and emerging instrument packages is clearly an advantage over existing systems composed of small instruments and bulky vacuum pumps. For example, the miniaturized mass spectrometer system currently under development at JPL lacks a similarly miniature or innovative vacuum pump. The need for vacuum pumps to be of small mass and volume and require low power are obvious for space and planetary exploration type missions. It is would also be advantageous to have a vacuum pump that is free of working fluids or lubricants that may contaminate sensitive instrument packages. Based on these issues and foreseen mission requirements it is obvious that future MEMS vacuum pumps will not be simply scaled-down versions of conventional vacuum pumps. Thus, the Knudsen Compressor is an attractive candidate for space missions requiring a MEMS vacuum pump.

III. Analysis of a Thermal Transpiration Vacuum Pump

The analysis presented here is a summary of a detailed analysis presented by Vargo et. al.[2] and Muntz et. al.[3] A Knudsen Compressor generates large changes in pressure by utilizing a cascade of multiple stages. Each stage is composed of a capillary and connector section. A temperature increase across the capillaries results in a thermal transpiration driven pressure increase. The capillary section is followed by a connector section where the pressure is approximately constant while the temperature drops to its original value entering the stage. Fig. 1 outlines an illustrative single stage of a Knudsen Compressor with the noted nomenclature described below. The analysis of a Knudsen Compressor's performance

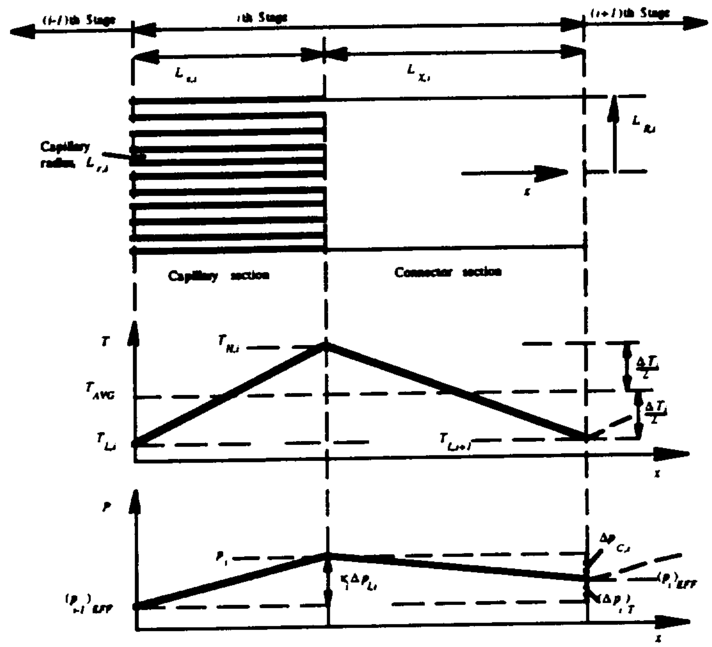

Figure 1: An illustrative single stage of a Knudsen Compressor.

is based on transitional flow modeling in the various sections of the system and provides realistic estimates for a wide range of operating conditions.

In a given cascade it is assumed that the average temperature is $T_{AVG} = T_{AVG,i} = T_{AVG,C,i}$, where i is the stage number. The subscript i also refers to the capillary section unless noted otherwise and the subscript C refers to the connector section. It follows that the absolute temperature difference across the ith stage is $|\Delta T_i| = |\Delta T_{C,i}|$ and it is assumed that $p_{AVG,i} = p_{AVG,C,i}$, the average pressure in the capillary section of stage i. The resulting expression for the stage pressure ratio is

$$P_i = 1 + \frac{p_{AVG,i}}{(p_{i-1})_{EFF}}\left[\frac{|\Delta T_i|}{T_{AVG}}\left\{\frac{Q_{T,i}}{Q_{P,i}} - \frac{Q_{T,C,i}}{Q_{P,C,i}}\right\} - 2\dot{M}_{DES} \times \dots\right.$$
$$\left.\dots\frac{A_1 p_{AVG,1}}{F_i A_i p_{AVG,i}}\left\{\frac{(L_x/L_r)_i}{Q_{P,i}} + \frac{(L_X/L_R)_i}{(F_{C,i}/F_i)(A_{C,i}/A_i)Q_{P,C,i}}\right\}\right] \qquad (1)$$

where $(p_{i-1})_{EFF}$ is the exit pressure of the (i-1)th stage or the entering pressure to the ith stage and Q_T and Q_P are the thermal transpiration and Poiseuille flow coefficients of each section, respectively. These flow coefficients are functions of the Knudsen number, Kn, and have been calculated for a large range of Kn s for cylindrical tubes[2]. The Knudsen number can be found from $Kn = (kT_{AVG})/(\sqrt{2}\Omega p_{AVG}L_r)$ with k and Ω being Boltzmann's constant and the collision cross-section of the working gas, respectively. The dimensions L_x and L_r refer to the length and pore radius of the capillaries. The upper-case subscript designates the connector section and the lower-case subscript designates the capillary section. F is the fractional open area and A is the cross-sectional area of a section. $\tilde{\dot{M}}_{DES}$ is the non-dimensional design mass flow derived from $\dot{M}_{DES} = \tilde{\dot{M}}_{DES}[2p_{AVG,1}((2kT_{AVG})/m)^{-1/2}A_1]$. The pressure ratio $p_{AVG,i}/(p_{i-1})_{EFF}$ is

$$\frac{p_{AVG,i}}{(p_{i-1})_{EFF}} = 1 + \frac{1}{2}\left[\frac{|\Delta T_i|}{T_{AVG}}\frac{Q_{T,i}}{Q_{P,i}} - 2\tilde{\dot{M}}_{DES}\frac{A_1}{F_iA_i}\frac{p_{AVG,1}}{p_{AVG,i}}\frac{(L_x/L_r)_i}{Q_{P,i}}\right] \tag{2}$$

and to a good approximation for efficient operating conditions

$$\frac{p_{AVG,1}}{p_{AVG,i}} = \left(\prod_{s=1}^{i-1} P_s\right)^{-1} \tag{3}$$

Here it is understood that for $i = 1$, $p_{AVG,1}/p_{AVG,i} = 1$.

The relationship between P_i and $\tilde{\dot{M}}_{DES}$ in Eq. 1 can be used to define a maximum mass flow $\tilde{\dot{M}}_{MAX}$ for a cascade. Since the first stage of the cascade controls the mass flow for the entire cascade under all reasonable operating conditions ($P_i \geq 1$), setting i = 1 and $P_1 = 1$ in Eq. 1 gives

$$\tilde{\dot{M}}_{MAX} = \left(\frac{F_1}{2}\left[\frac{|\Delta T_1|}{T_{AVG}}\left\{\frac{Q_{T,1}}{Q_{P,1}} - \frac{Q_{T,C,1}}{Q_{P,C,1}}\right\}\right]\right) \Big/ \left[\frac{(L_x/L_r)_1}{Q_{P,1}} + \frac{(L_X/L_R)_1}{(F_{C,1}/F_1)(A_{C,1}/A_1)Q_{P,C,1}}\right] \tag{4}$$

For all applications of the Knudsen Compressor $\tilde{\dot{M}}_{DES} = \beta\tilde{\dot{M}}_{MAX}$ with β having a value between 0 and 1. Initial simplified studies of energy use per unit mass flow indicate a β of about 0.5 is appropriate. The pressure ratio generated for a cascade of N stages is

$$(\wp_N)_{DES} = \prod_{i=1}^{N} P_i \tag{5}$$

The energy consumption for a block of N stages can be found directly from

$$\dot{Q}_N = \sum_{i=1}^{N}\left[\frac{|\Delta T_i|K_i(1-F_i)A_i}{L_{x,i}}\right] \tag{6}$$

where K_i is the thermal conductivity of the capillary membrane material. Thermal losses through the membrane are assumed to dominate the energy use. The cascade's volume can be found from

$$V_B = \sum_{i=1}^{N}[A_iL_{x,i} + A_{C,i}L_{X,i}] \tag{7}$$

The low pressure pumping speed or the volume flow rate through the first stage can be written as

$$\dot{V} = \frac{A_1\left[F_1\beta\frac{|\Delta T_1|}{T_{AVG}}\sqrt{\frac{kT_{AVG}}{2m}}\right]\left\{\frac{Q_{T,1}}{Q_{P,1}} - \frac{Q_{T,C,1}}{Q_{P,C,1}}\right\}}{\left\{\frac{(L_x/L_r)_1}{Q_{P,1}} + \frac{(L_X/L_R)_1}{(F_{C,1}/F_1)(A_{C,1}/A_1)Q_{P,C,1}}\right\}} \qquad (8)$$

IV. MEMS Knudsen Compressor Fabrication

This section focuses on utilizing MEMS based fabrication techniques to design, fabricate and assemble a prototype Knudsen Compressor suitable for use in known MEMS in-situ instruments at MDL. A single stage device will be constructed in order to test new compressor materials as well as develop a fabrication and assembly approach for a Knudsen Compressor cascade. The single stage MEMS Knudsen Compressor design is shown in Fig. 2. This device is composed of seven parts that are bonded to one another. These parts include hot and cold side silicon thermal guards, a transpiration membrane, two Pyrex® 7740 plenums and two Pyrex gas feedthroughs with the single stage construction similar in layout to the previous experimental compressors[2]. Fabrication and assembly of the single stage parts will be discussed below.

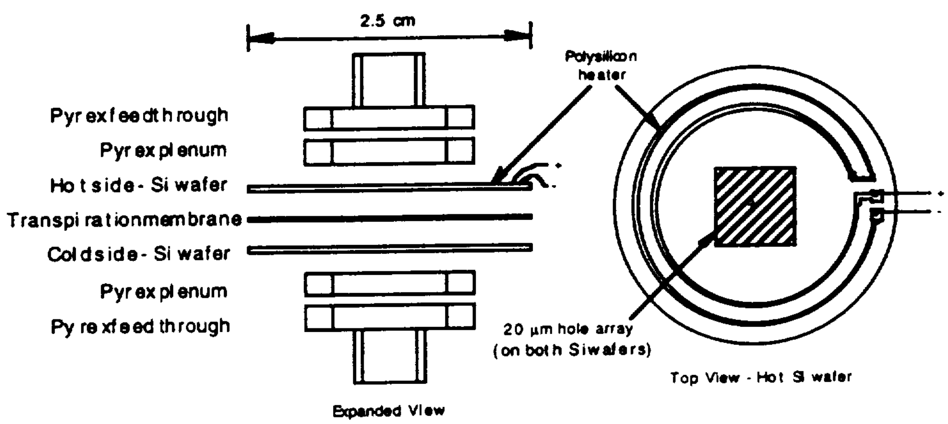

Figure 2: Single stage MEMS Knudsen Compressor design.

Thermal guards, which have a dense array of holes to allow for gas transmission, are utilized in the Knudsen Compressor in order to ensure that molecules near the transpiration membrane faces are at known and set temperatures. The thermal guards are fabricated in silicon, which has a high thermal conductivity (157 W/mK) to ensure temperature uniformity, using a high-aspect ratio anisotropic etch system. The hot and cold thermal guards are each made from a 400 µm thick silicon wafer with each guard having a dense array of 20 µm diameter cylindrical tubes (i.e. holes) etched in a central 0.5 cm^2 area (Fig. 2). Each hole array area contains nearly 56,000 holes with a hole separation of 10 µm. The diameter of 20 µm was selected for ease of fabrication and to ensure that these thermal guards provided the same function as previous guards[1]. The holes are etched using an innovative deep reactive ion etching (DRIE) system available at MDL. This etching system, which is manufactured by Surface Technology Systems, Inc., provides highly anisotropic etch capability in silicon. The fabrication of etched silicon structures results from the utilization of time-multiplexed, inductively coupled plasmas of SF_6 and C_4F_8 gases[4]. The desired etch areas (i.e. the holes) on the wafers are first patterned in photoresist using standard MEMS fabrication techniques prior to DRIE. Etching of silicon occurs during the SF_6 plasma step where a fluorine-rich environment chemically reacts with and removes exposed silicon from the wafer. The C_4F_8 step is used to control the anisotropy of the etching by passivating the sidewalls of the etched features. This step helps to prevent lateral etching (i.e. undercutting) of the etched features and the mask layer during the next etch step. The DRIE system can provide silicon etching rates up to 5 μm/min, aspect ratios of 30:1 and sidewall angles of 90±<0.25°. Fig. 3 is a scanning electron microscope micrograph of the fabrication of the thermal guard tubes.

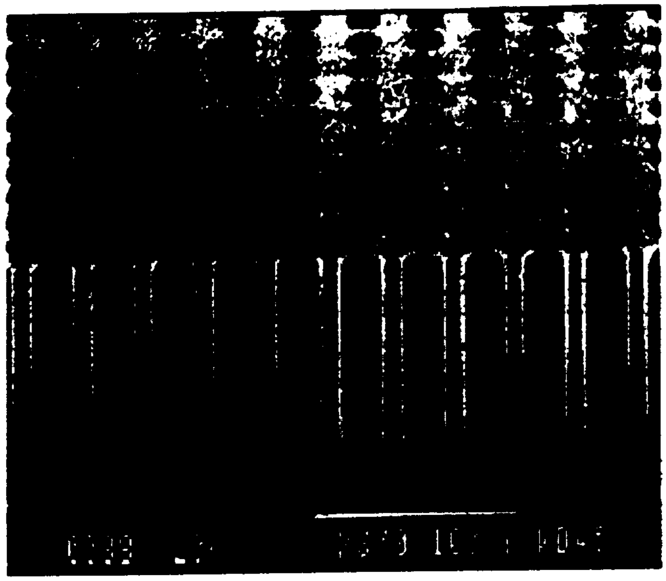

Figure 3: Scanning electron micrograph of the thermal guard tube array fabrication using the DRIE.

The actual heating element of the designed single stage device consists of deposited and patterned 0.4 μm thick polysilicon layer that is placed on the unbonded area of the hot side thermal guard (Fig. 2). The cold side wafer is not actively cooled and is allowed to reach equilibrium with the local environment, albeit with some amount of heat transferring through the transpiration membrane. The polysilicon material has a prescribed resistance (set by doping level, layer thickness and pattern) which acts a resistive path to an applied current. Depending on the current applied across the ends of the heater, it resistively heats to a desired T_H needed for stage operation. This heater implementation is simple and takes advantage of silicon's relatively high thermal conductivity in transferring this temperature to the attached transpiration membrane.

An established temperature difference across the transpiration membrane provides gas pumping in the Knudsen Compressor. Due to ongoing patent issues we are not able to discuss the actual membrane material used in this project. The main properties required of a transpiration membrane are to have a low thermal conductivity (to minimize heat transferal) and have micro and nano-size pores (to establish rarefied flow conditions).

All of the elements in the stage will be bonded together to provide a vacuum tight system. The Pyrex pieces are conventionally machined and have sufficient surface flatness to be bonded to adjacent components in the stage. Each thermal guard will be anodically bonded to its adjoining Pyrex plenum. Anodic bonding is a commonly used method for joining glass to silicon for micromechanical applications[5]. Each Pyrex plenum is epoxy bonded to a gas feedthrough made of Pyrex. Each feedthrough has an attached stainless steel tube which allows for the securing of a leak-tight gas fitting. The transpiration membrane will be pressure bonded to the thermal guards. Pressure bonding is the method of joining two wafers by way of pressure and high temperature.

The single-stage device of Fig. 2 is the first implementation of MEMS fabrication methods in Knudsen Compressor construction. Fabrication and assembly of the single stage device are ongoing and will be reported in a later publication. A cascade incorporating several stages will also be constructed and tested.

V. Application to In-Situ Instruments

In-situ instruments are one application where integrated and novel MEMS vacuum pumps would be of great benefit. Vacuum pumps that have no fluids or lubricants would be ideal additions for these instruments in order to avoid contamination issues. Minimizing or eliminating the number of moving components in a MEMS vacuum pump would also be advantageous especially for space applications. As a result of these requirements, the Knudsen Compressor discussed here is an attractive device choice. Several applications where a MEMS Knudsen Compressor vacuum pump would apply are included in this section.

Microscale Vacuum Pump Example

A numerical code utilizing the transitional flow analysis summarized in Sec. III has been used to provide estimates of Knudsen Compressor performance for a range of inputs and cascade settings[2]. In this section the results for a microscale configuration of a Knudsen Compressor vacuum pump and an application are presented. The performance estimates for a vacuum pump depend on the values assigned to the many parameters needed to define a cascade. Thus, the results only give an indication of expected performance for the selected pumping task. The formidable job of defining optimum pump configurations subject to a variety of practical and theoretical constraints is currently being addressed.

Assume that a microscale vacuum pump is needed to pump from an initial low pressure (p_0) to atmospheric pressure (760 Torr). Also assume that the pump is pumping nitrogen with the following inputs constant per stage: $T_{AVG} = 293K$, $\Delta T = 100K$, $F_i = 0.6$, $F_{C,i} = 1.0$ and $\beta = 0.5$. The pump is segmented into two sections with the first or low pressure section pumping from p_0 to a cut-off pressure and the second or high pressure section providing the remaining pumping needed to reach one atmosphere. In the simulation the low pressure section has the dimension $L_{r,1}$ set to an initial value ($L_{r,1} = 500$ μm) and $L_R/L_r = 5$. In both pump sections $L_{r,i}$ decreases as the cascade pressure increases in order to maintain a constant Kn_i. The first stage ends when the cascade pressure reaches a pre-determined cut-off pressure of 10 mTorr. At this point the second section of the Knudsen Compressor performs the remaining pumping to atmosphere. In the second section the $L_{r,1}$ is set to the first section's initial value and $L_{r,i}$ once again decreases under constant Kn_i (in this section Kn_i is much lower) until the pressure reaches 1 atm. For this example, each stage of the pump has constant values of $L_{x,i}$, $L_{R,i}$, $L_{X,i}$ and $A_i = A_{C,i}$ which equal their first stage values for each section of the pump. Table 1 provides a summary for this microscale vacuum pump example along with several important measures of pump performance: the energy use per molecule of upflow, $\dot{Q}/\dot{N}$ and the cascade volume per molecule of upflow, $V/\dot{N}$. It is of interest to note that as the input pressure decreases in the pump the power use and volume of the pump increase. This suggests that there will be a limit to the ultimate pressure attainable with a given vacuum pump due to allowable power or size constraints.

Based on the results outlined in Table 1 it is possible to characterize a general microscale pump for use with a typical micro mass spectrometer. Assume that the mass spectrometer requires a molecule flow rate of 5×10^{14} molecules/sec. The resulting important cascade characteristics are: for $p_0 = 1$ mTorr, $\dot{Q} = 2.4$ W and $V = 13.9$ mL; and for $p_0 = 10$ mTorr, $\dot{Q} = 28.5$ mW and $V = 0.16$ mL. The resulting vac-

Table 1: Summary of numerical results for a microscale vacuum pump.

p_0, $mTorr$	$\frac{\dot{Q}}{\dot{N}}$, $\frac{W}{\left(\frac{mol}{s}\right)}$	$\frac{V}{\dot{N}}$, $\frac{mL}{\left(\frac{mol}{s}\right)}$
0.1	1.09E-12	6.13E-12
1	4.89E-15	2.77E-14
10	5.70E-17	3.27E-16

uum pump configurations result in reasonable power and size values for this application.

JPL Mass Spectrometer

An interesting application of the Knudsen compressor is to provide dynamic pumping for a meso/microscale mass spectrometer. For example, D. Wiberg of MDL has LIGA fabricated a quadrupole array for a miniaturized mass spectrometer that has a diameter of 3 cm, length of 4 cm and operational pressures of up to a maximum of 1 mTorr[6]. A Knudsen Compressor that provides pumping for the miniaturized mass spectrometer on a Martian atmospheric sampling task can be designed with the assistance of the analysis presented in Sec. III.

Assume that the selected mesoscale Knudsen Compressor will have to provide pumping on Mars from 10 mTorr to atmospheric pressure (5.25 Torr). Initial minimum energy use calculations for this task result in selecting a pressure ratio of 10 for three segments of 8 stages each (Table 2). Also, assume that this attached vacuum pump provides a uniform gas flow rate through the mass spectrometer. A constant flow rate can be maintained across stages in a Knudsen Compressor by reducing the stage area as the input pressure to the stage increases (i.e. $A_i = A_1 / P_i^{i-1}$) thereby implying a tapered design. Table 2 contains results for a Knudsen Compressor pump with three stacked layers or segments (one segment for each $P_i = 10$) that provide the required pumping.

Table 2: Operating characteristics of a 3 x 8 stacked pump.

Segment	p_{min} to p_{max}	Characteristic dimension (cm)	Power requirement (mW)
1	10 mTorr to 100 mTorr	2	71.4
2	100 mTorr to 1 Torr	0.2	7.1
3	1 Torr to 10 Torr	0.02	0.7

For all segments, the values of F_B and $L_{r,i}$ are assumed to be 0.6 and 1 μm, respectively. For this example, an average Mars surface temperature of T_L = 210 °K serves as each cold side thermal guard temperature source. Hot side temperatures are provided by integrated heaters or by the utilization of waste heat generated by co-located electronics. The flow component mass was chosen to be $m = 7.3 \times 10^{-26}$ kg since Mars has an atmospheric composition of 95.3% CO_2. For the right-hand column of Table 2, the power estimate for each segment is based on providing a molecule flow rate of 2×10^{14} molecules/sec (based on changing the mass spectrometer's operational volume of 30 cm^3 every second at a pressure of 0.1 mTorr) through each segment of 8 stages and p_0 for each segment specified by the pressure increase from the previous segment. A mesoscale Knudsen Compressor vacuum pump with a volume of about 30 cm^3 that requires about 80 mW is envisioned for the miniaturized mass spectrometer system. The envisioned vacuum pump was sized as a roughing pump for the mass spectrometer, however it is not clear that the mass spectrometer needs an additional high vacuum pump. Actual operation of the mass spectrometer may dictate the vacuum levels needed for a particular application.

JPL Atmospheric Electron X-ray Spectrometer

Recently, a proof-of-concept demonstration of the Atmospheric Electron X-ray Spectrometer (AEXS) was performed at MDL[7]. The AEXS is a novel, miniature instrument capable of performing chemical (elemental) analysis by the excitation and detection of characteristic x-rays from a sample using electron irradiation. It falls in the same class of miniature instruments as the Alpha Proton X-ray Spectrometer (APXS) that was successfully used on the Sojourner rover in the Mars Pathfinder Mission. The APXS uses alpha particles for the excitation of characteristic x-ray fluorescence and takes several hours to acquire a spectrum. In contrast, the spectrum acquisition time of the AEXS is estimated to be less than a minute, due to the higher electron fluxes that are available. Previous electron-beam based instruments could not be significantly miniaturized, because they required mechanisms for handling samples and for their introduction into a vacuum chamber. The vacuum pumping requirement also set limits on the minimum mass and power consumption for these instruments. The AEXS is a non-contact analysis technique, which does not require sample preparation and has a projected mass of 0.7 kg and an energy consumed per spectrum acquisition of 50 J. The results of recent experiments and the future development plan will be discussed and presented in a future publication by T. George[7] and others at MDL.

The AEXS instrument is a miniature sized instrument that needs dedicated and integrated vacuum pumps for a space mission. The detector and the electron source components of this instrument require high vacuum conditions to operate. Ion pumps have been investigated in order to provide high vacuum levels but an additional roughing pump is needed in order to back the ion pump (provide pumping from low vacuum to atmospheric pressures) especially for Earth applications. The Knudsen Compressor is an attractive roughing pump for this application. MEMS vacuum pumps integrated into this instrument would provide a fully functional in-situ instrument, however vacuum pumps for the AEXS system are currently under study. A near-term application for this instrument would be for elemental analyses on future Mars missions.

VII. Summary

Future missions utilizing vacuum pumped in-situ instruments will most likely require novel and integrated MEMS based vacuum pumps. Many conventional vacuum pumps are incapable of being simply scaled down due to complex moving components and a dependence on working fluids and lubricants. The MEMS Knudsen Compressor is an attractive vacuum pump for several space exploration instruments since it has no moving parts and no dependence on fluids or lubricants. Example calculations for this vacuum pump resulted in a pump of low energy use, small volume and mass, all of which are preferential for space applications.

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References

1. S.E. Vargo and E.P. Muntz, E.P., A Simple Micromechanical Compressor and Vacuum Pump for Flow Control and Other Distributed Applications, AIAA-96-0310 (1996).
2. S.E. Vargo, E.P. Muntz, G.R. Shiflett and W.C. Tang, The Knudsen Compressor as a Micro and Macroscale Vacuum Pump Without Moving Parts or Fluids, J. Vac. Sci. Technol. A, Jul/Aug (1999).
3. E.P. Muntz, Y. Sone, K. Aoki and S. Vargo, Performance Analysis and Optimization Considerations for a Knudsen Compressor in Transitional Flow, USCAME Report No. 98001 (1998).
4. J. Bhardwaj and H. Ashraf, Advanced Silicon Etching Using High Density Plasmas, Micromachining and Microfabrication Process Technology - SPIE, 2639, 224-233 (1995).
5. K.B. Albaugh, P.E. Cade and D.H. Rasmussen, Mechanisms of Anodic Bonding of Silicon to Pyrex® Glass, Int. Workshop on Solid-State Sensors and Actuators, Hilton Head, SC, 109-110 (1988).
6. D.V. Wiberg, M.H. Hecht, O.J. Orient, A. Chutjian, K. Yee and S. Fuerstenau, A LIGA Fabricated Quadrupole Array for Mass Spectrometry, High Aspect Ratio MicroStructure Technology meeting, Madison, WI (1997).
7. T. George, Proof-of-concept of the Atmospheric Electron X-ray Spectrometer, personal communication (March 1999).

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References

1. S.E. Vargo and E.P. Muntz, E.P., A Simple Micromechanical Compressor and Vacuum Pump for Flow Control and Other Distributed Applications, AIAA-96-0310 (1996).
2. S.E. Vargo, E.P. Muntz, G.R. Shiflett and W.C. Tang, The Knudsen Compressor as a Micro and Macroscale Vacuum Pump Without Moving Parts or Fluids, J. Vac. Sci. Technol. A, Jul/Aug (1999).
3. E.P. Muntz, Y. Sone, K. Aoki and S. Vargo, Performance Analysis and Optimization Considerations for a Knudsen Compressor in Transitional Flow, USCAME Report No. 98001 (1998).
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5. K.B. Albaugh, P.E. Cade and D.H. Rasmussen, Mechanisms of Anodic Bonding of Silicon to Pyrex® Glass, Int. Workshop on Solid-State Sensors and Actuators, Hilton Head, SC, 109-110 (1988).
6. D.V. Wiberg, M.H. Hecht, O.J. Orient, A. Chutjian, K. Yee and S. Fuerstenau, A LIGA Fabricated Quadrupole Array for Mass Spectrometry, High Aspect Ratio MicroStructure Technology meeting, Madison, WI (1997).
7. T. George, Proof-of-concept of the Atmospheric Electron X-ray Spectrometer, personal communication (March 1999).